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The Basics of Food Irradiation

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Comments (Optional):

MR BIRD WAS INVOLVED WITH THE SENIOR NE DESIGN COURSE WHICH PRODUCED A CONCEPTUAL DESIGN OF A FOOD IRRADIATION FACILITY. THIS THESIS FOR THE HONORS PROGRAM NICELY COMPLEMENTS THE WORK DONE FOR THE DESIGN PROJECT.

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ABSTRACT

With the growing public concern over food safety and foodborne diseases, there has been increased pressure on both the government and the various food processing industries to ensure the safety of the food supply. After recent outbreaks of as *Escherichia coli* O157:H7 in the Pacific Northwest, the safety of red meat has been of prime concern to many consumers. Gamma irradiation is a promising technology that has been proven to safely eliminate *E. Coli* and many other common foodborne pathogens. Irradiation technology also has the added benefit of extending the shelf life of irradiated food products, which could significantly reduce the amount of food that is lost to spoilage, particularly in third world countries.

The technology used for irradiation has been proven to be sound over the past four decades, being used extensively on medical supplies, spices, and other products in many countries throughout the world. The main challenge is to convince the public that this technology is beneficial, and indeed necessary to ensure their safety. While market studies have shown that many consumers are willing to purchase irradiated foods, many others are not. Education programs would increase the numbers willing to purchase the irradiated products, though a small number of consumers are still adamantly opposed to the process even after such educational programs. However, it remains to be seen whether or not food irradiation will be commercially viable in the United States.

INTRODUCTION

In the early 1950's, research began on the application of ionizing radiation to food products. By 1960, irradiation processing technology was ready for commercial application. However, the 1958 passage of the Food Additives Amendment to the Food, Drug, and Cosmetic Act effectively delayed the commercialization the process for more than three decades. This amendment classified radiation sources as food additives, thus requiring an authorizing regulation prescribing safe conditions of use and pre-market review and acceptance by the Food and Drug Administration (FDA).[1] Since 1963, the FDA has approved the use of ionizing radiation on more than a dozen specific types of food (see Table 1).[1,2]

Table 1 FDA and USDA approvals for irradiated foods

Product	Agency	Date	Dose (kGy)	Purpose
Wheat, wheat flower	FDA	1963	0.2-0.5	Insect disinfestation
White potatoes	FDA	1964	0.05-0.15	Sprout inhibition
Spice and vegetable seasonings	FDA	1983	Max. 10	Microbial Decontamination
Pork	FDA	1986	0.3-1.0	Trichinella Spiralis control
Fruits and vegetables	FDA	1986	Max. 1.0	Disinfestation and Ripening Delay
Papaya fruit	USDA	1987	Min. 0.15	Insect disinfestation
Herbs, spices, and dry vegetable seasonings	FDA	1986	Max. 30	Insect disinfestation and/or microbial decontamination
Dehydrated enzymes	FDA	1986	Max. 10	Microbial Decontamination
Animal and Pet food	FDA	1986	Max. 25	Microbial Decontamination
	FDA	1995	2-25	Salmonella Control
Poultry	FDA	1990	Max. 3.0	Microbial Decontamination
	USDA	1992	1.5-3.0	Microbial Decontamination
Meat, frozen, packaged	FDA	1995	Min. 44	Sterilization
Red meat, non-frozen	FDA	1997	Max. 4.5	Microbial Decontamination
Red meat, frozen	FDA	1997	Max. 7.0	Microbial Decontamination

Irradiation has been approved for at least one type of food product in nearly 40 countries throughout the world, including the United States, Belgium, France, South Africa, and the People's Republic of China.[1,3] Food irradiation has also been endorsed by many national and international organizations, including the World Health Organization (WHO), the American Medical Association (AMA), the Institute of Food Technologists, and the American Dietetic Association.[2] Currently, twenty-eight countries have commercially available irradiated foods, including spices, fruits, vegetables, rice, potatoes, onions, and sausage. Muscle foods, including poultry, pork, and red meats, have been approved for irradiation in 19 countries, including the France, Chile, and the Netherlands.[1]

In December 1997, the FDA approved the use of irradiation on red meat in both the fresh and frozen state. This approval was timely, due to the rising public concern over foodborne illnesses caused by pathogens such as *Escherichia Coli* O157:H7. The FDA approved the use of gamma radiation doses of up to 4.5 kiloGray (kgy) for refrigerated meat and 7.0 kGy for frozen meat.[1] One Gray is equal to one joule of energy deposited per kilogram of the medium.[4] The FDA also approved the use of X-rays with energies up to 5 million electron volts and electrons with a maximum energy of 10 million electron volts.[1]

While irradiation of food has not yet caught on in the United States, irradiation technology has been in use for years. There are more than 40 commercial irradiation facilities currently operating in the United States, and they have achieved an excellent safety record. Among the products that are currently irradiated are bandages, liquid detergents, medical instruments, syringes, contact lens cleaning solutions, and pet food. Obviously, the average American consumer is quite familiar with some or all of the items, meaning that most people handle irradiated products every day, whether they realize it or not.

THE IRRADIATION PROCESS

Three types of radiation are used in the irradiation process: gamma radiation, electron beams, and X-rays. Of the three, gamma irradiation is the most commonly used, so this section will focus on that technology. In the United States, two types of gamma radiation source have been approved for use in irradiation facilities: Cobalt-60 and Cesium-137. Cesium-137 has a melting point of approximately 28.4 ^{o}C, which is only slightly higher than room temperature. This could result in undesired melting of the radiation source. Also, Cesium-137 reacts with water, which could result in undesired chemical reactions occurring inside the radiation vault. Thus, Cobalt-60 is the most commonly used isotope for gamma irradiation.

MDS Nordion of Ontario, Canada is the world's leading supplier of Cobalt-60 sources for irradiation facilities. These sources take the form of Cobalt-60 "pencils" mounted in a stainless steel source rack (see Figures 1 and 2). The individual pencils are approximately 18 inches long and 0.4 inches in diameter. The radioactive material is doubly encapsulated, meaning that it is held inside two layers of material, ensuring proper containment at all times. A typical source pencil has a strength between 6,000 and 14,000 Curies ($2.22*10^{14}$ to $5.18*10^{14}$ disintegrations per second). The source pencils and racks are arranged according to the particular application in order to achieve the desired dose distribution in the product.

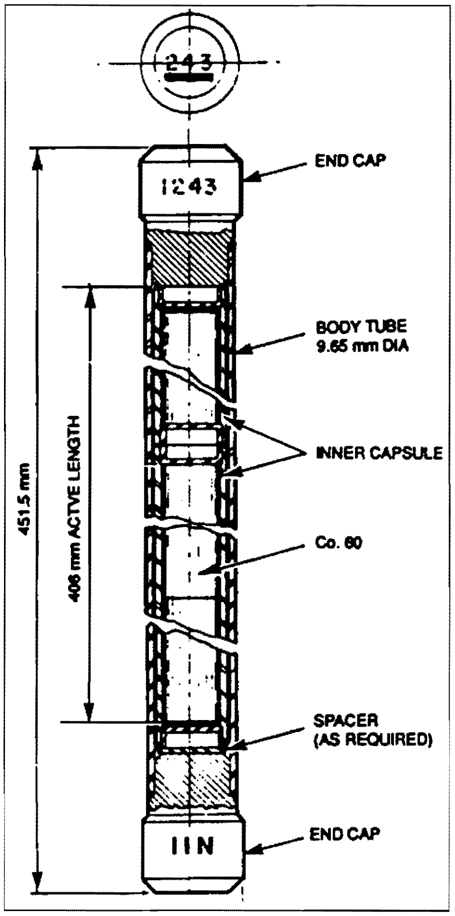

Figure 1 Cobalt-60 Source Pencil (Courtesy of Nordion International)

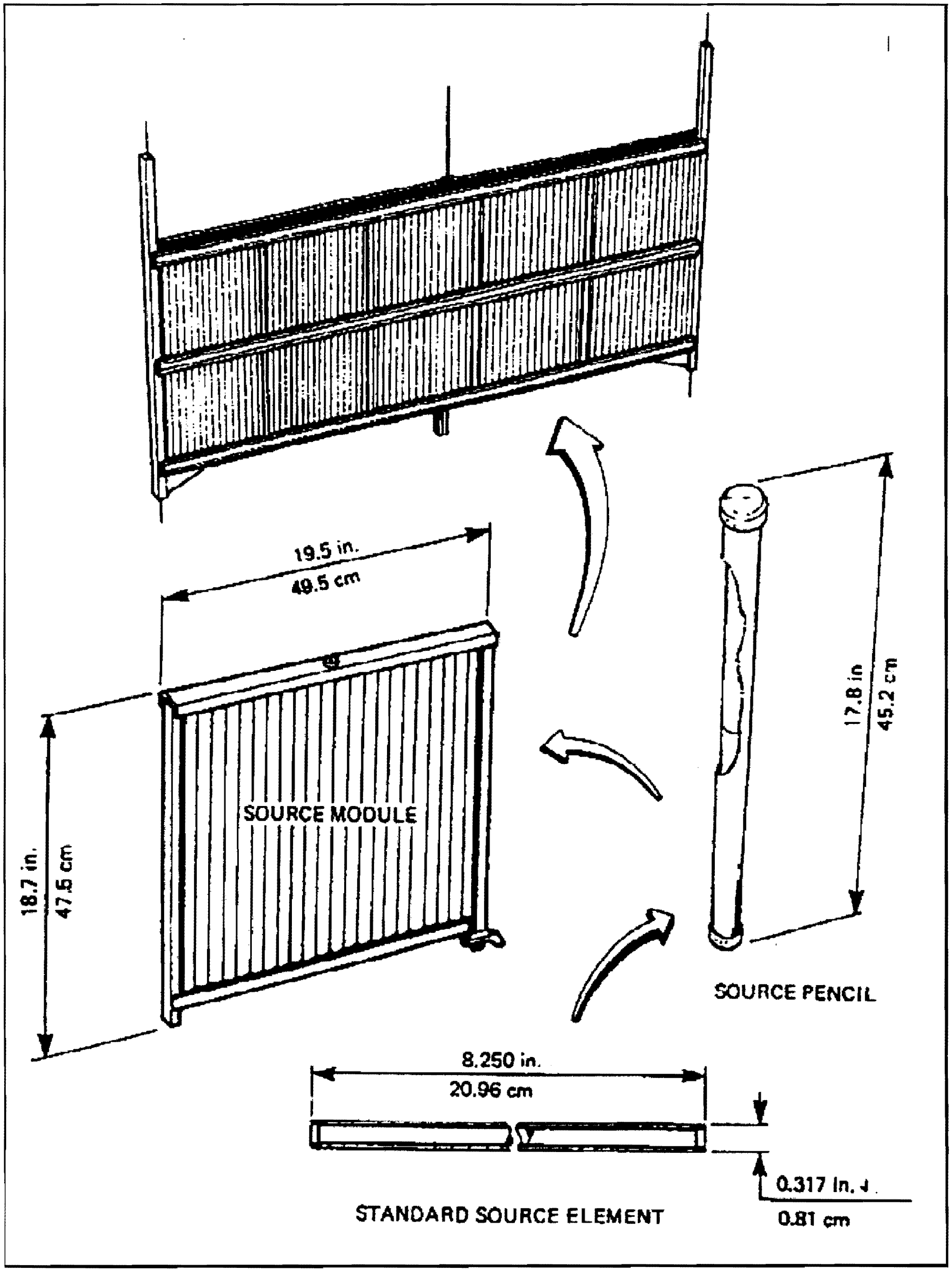

Figure 2 Cobalt-60 Source Rack (Courtesy of Nordion International)

Figure 3 shows a typical gamma irradiation facility. In this facility, the product to be irradiated is loaded onto the conveyor system and passed in front of the radiation source. Various methods can be used to account for attenuation of radiation through the product in order to ensure an even dose distribution. Some possibilities include turning the product to expose each side of the container or utilizing multiple sources to expose the product more evenly. After passing through the irradiation room, the conveyor system carries the product to the unloading area, where it can be loaded onto trucks for shipping. Typically, some for of radiation dosimetry device is passed through the irradiator with the product to ensure adequate quality control.

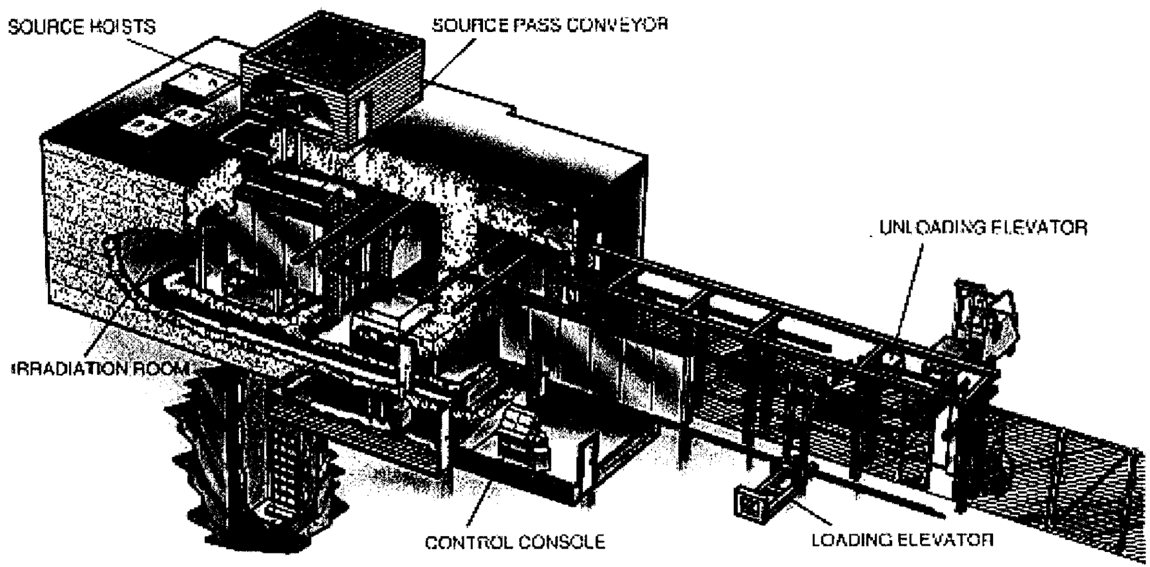

Figure 1: JS-8900 Unit Carrier Irradiator

Figure 3 Typical Gamma Irradiation Facility (Courtesy of Nordion International)

While the irradiator is in use, monitoring and observation are done through a system of closed-circuit television cameras and/or a radiation-shielded viewing window in the control room. Closed-circuit camera systems are generally more cost-effective and allow for a more complete view of the facility. Thus, camera systems are used more often than the more expensive viewing windows. When in use, the Cobalt-60 source rack can be lowered into a storage pool. This pool provides radiation shielding, which allows the workers to safely enter the irradiation room to perform maintenance and other tasks.

BENEFITS OF FOOD IRRADIATION

Though foodborne illnesses are largely preventable, they remain a serious health problem in the United States and throughout the world.[4] Pathogenic bacteria such as *Campylobacter, Escherichia Coli* O157:H7, *Salmonella, and Listeria Monocytogenes* cause thousands of deaths and millions of cases of diarrheal disease each year in the United States alone (see Table 2).[5] The economic loss due to foodborne disease has been estimated to be as high as $5 billion to $6 billion annually. In addition, the public has been alarmed by several recent outbreaks of *E. Coli* O157:H7 in hamburger, particularly in the northwestern United States.[4]

Table 2 Foodborne pathogens in the United States, 1993

Pathogen	Total Cases	Total Deaths
Campylobacter Jejuni or Coli	2,500,000	200 – 730
Clostridium Perfringens	10,000	100
Listeria Monocytogenes	1795-1860	445 – 510
Salmonella	800,000 - 4,000,000	800 - 4,000
Escherichia Coli O157:H7	10,000 - 20,000	200 – 500
Staphylococcus Aureus	8,900,000	7120
Toxoplasma Gondii	4,111	82

Irradiation has been shown effective in combating several of these pathogens, including *Escherichia Coli* O157:H7 and *Salmonella*, both of which are of tremendous concern to the public. Table 3 shows the radiation doses required to reduce the population of various foodborne pathogens in beef at 5° Celsius.[4]

Table 3 Radiation doses to reduce pathogen populations by 90%

Pathogen	Dose (kGy)
Bacillus cereus	2.46 ± 0.31
Campylobacter Jejuni	0.16-0.20
Clostridium Botulinum	3.43 @ -30 °C
Escherichia coli O157:H7	0.30 ± 0.02
Listeria Monocytogenes	0.45 ± 0.03
Salmonella	0.70 ± 0.04
Staphylococcus Aureus	0.46 ± 0.02

A radiation dose of 2.5 kGy at 5 °C would eliminate more than 99.9999% of *Campylobacter*, 99.999% of *Escherichia* O157:H7, 99.9% of *Salmonella*, and 99.999% of *Staphylococcus Aureus* cells.[4]

In addition to the health benefits described above, food irradiation also extends the shelf life of food products. Irradiation technology could help significantly reduce the food losses due to insect infestation, spoilage, or sprouting.[6] In addition, the elimination of foodborne pathogenic bacteria would also reduce dependence upon refrigeration. This is particularly important in reducing food losses in developing countries, where adequate refrigeration facilities are too expensive or simply do not exist.[7]

For example, in South and Southeast Asia, refrigeration (at 2-4 °C) is normally used to control the rotting and sprouting of potatoes. Refrigeration is effective for long-term storage, but it is a high-cost method used to preserve relatively low-cost products. Irradiation at 0.1-0.15 kGy combined with mild refrigeration (10-15 °C) would be a more cost-effective method to control rotting and sprouting for long-term storage.[7]

Another important possibility for the use of food irradiation comes as a result of increasing concerns over the environmental effects of chemical fumigation. Many of the more common chemicals used, such as Ethylene Dibromide (EDB), Methyl Bromide (MB), and Ethylene Oxide (ETO), have either been prohibited or are facing increasing restrictions in advanced countries. The U.S. Environmental Protection Agency (EPA) banned the use of EDB in the United States in 1984. The importation of foods treated with EDB has also been prohibited. Many other countries have followed the U.S. by banning the use of EDB for disinfestation of food and food ingredients. MB is currently the most widely used fumigant for food and agricultural products against insects. However, the Montreal Protocol of 1992 lists MB as an ozone-depleting chemical. According to the Montreal Protocol, production of all such chemicals will be illegal after the year 2000.[7] ETO was banned by the European Community starting in January 1991 due to worker-safety concerns. ETO vapors are toxic to man in the concentrations used for fumigation and can form flammable and/or explosive mixtures with air. Also, there is a danger of chemical residues remaining in the food. Since the European ban on the use of ETO, other countries, including the United States, have also been under pressure to ban the chemical.[7]

The loss of these chemical fumigants will force the food processing industry to look for new methods to ensure the safety of their products. The outlook for new chemical alternatives does not look promising, which may leave radiation as the most attractive alternative. Studies have already shown that irradiation, at doses typically between 0.2 and 0.7 kGy, is effective as a replacement for the most-commonly used fumigants, and in many cases is more economical than the currently used methods.[7]

COST/BENEFIT CONCERNS

The benefits of food irradiation are obvious. However, it is important to weigh these benefits against the costs involved in the commercialization of the irradiation process. Three questions have to be answered before food irradiation will find commercial success in the United States. First, how much does it cost? The actual cost per unit is of prime concern to food producers, distributors, and retailers, many of whom operate with the slimmest of profit margins. Second, is the public willing to buy and eat irradiated foods? Finally, if consumers are willing to buy irradiated foods, how much are they willing to pay for the process?

The first question is fairly simple. Studies have shown that capital costs for a typical gamma irradiation facility can run anywhere between approximately $1.8 and $6.9 million.[8, 9] The former number represents the cost of a facility for low-dose (min. 0.15 kGy) irradiation of fruits and grains.[8] The latter represents the cost of a facility to irradiate red meat to the FDA prescribed doses.[9] Unit costs can range from $0.007 per pound for fruits and grains up to around $0.05 per pound for red meat.[8,9]

Typically, the costs are driven mainly by the source requirements for the particular application. For fruits and grains, the low doses needed allow for a smaller source, typically between 50,000 and 90,000 Curies, depending on the particular configuration and application.[8] For red meat, the higher required doses necessitate much larger sources, on the order of three million Curies.[9] This affects not only the initial capital costs, but the annual operating costs as well. A typical gamma irradiation facility will require the replacement of about twelve to thirteen percent of its source each year to account for the decay of the Cobalt-60. At a price of $1.46 per Curie[8], this can represent a very significant cost, particularly in the larger facilities that would be used to irradiate red meat.

The second question is somewhat more difficult to answer. However, the issue of public acceptance must be addressed before food irradiation will be commercially viable in the United States. Several studies have indicated that consumers are willing to buy irradiated foods. In fact, studies and market tests have shown that informed consumers are willing to pay a premium for irradiated pork and poultry. However, popular opinion seems to be that most people are opposed to irradiation.[2]

One 1989 study presented results that were highly in favor of food irradiation. Initial surveys showed that over 60% of respondents were likely to try irradiated foods. About one third were unwilling to try irradiated foods, with about five percent of respondents being undecided. After this initial survey, the study group listened to a presentation on food irradiation. The presentation included: an explanation of the irradiation process in both technical and non-technical terms, a presentation of arguments for and against food irradiation, and a short history of food irradiation. After this presentation, more than 75% of respondents said they were likely to try irradiated foods, and only 22% were still unwilling to try the irradiated products.[10]

These results seem to show that the public is very much in favor of food irradiation. However, in this same study only 53% of respondents said that they would feel comfortable serving irradiated foods to their families. Also, nearly

40% said that they would support legislation to ban all irradiated foods from the U.S. market, and 60% said that they believed that most other people would support such a ban.

Another 1989 study showed that about 44% of people would be willing to buy irradiated foods. In this study, 22% were unlikely to buy irradiated foods, with the remaining 34% being undecided.[11] The discrepancies between these results and those of the previous survey serve to demonstrate the need for caution in interpreting statistical results. Results are nearly always skewed by the demographics of those surveyed and the manner in which the questions are presented. A comprehensive nationwide survey would serve to clarify the public's position on this issue. However, such a survey would be difficult due to the costs and time requirements involved.

One much simpler way to gauge the public's reaction to irradiated foods is to perform market tests. Several such tests have been done in the United States in recent years, with generally favorable results. In these tests, the major factor favoring the irradiated food products has been the appearance of superior quality and safety. None of these tests revealed any evidence that informed consumers will not accept irradiated foods.[12]

In March 1987, a shipment of Hawaiian papayas was irradiated in Los Angeles at a dose of 0.41-0.51 kGy to satisfy quarantine regulations. These papaya were then sold alongside hot-water dipped papaya at two supermarkets in Anaheim and Irvine, California. By the end of the day, 60 kilograms of irradiated papaya had been sold, compared to only 5.1 kilograms of hot-water dipped fruit, a ratio of better than 11:1 in favor of the irradiated product. Two-thirds of customers in Anaheim and four-fifths of those in Irvine said that they would buy irradiated papaya again.[12]

In January 1992, irradiated strawberries were successfully market-tested in Miami Beach, Florida. Results showed that when priced the same, irradiated strawberries sold at about the same rate as non-irradiated strawberries. Later in the week, when a new shipment of non-irradiated strawberries was purchased at a higher price, the irradiated strawberries actually sold better than the more expensive non-irradiated variety.[13] A similar market test was conducted in Chicago during March 1992. Over a three-day period, Carrot Top, Inc. sold 172 cases of irradiated strawberries and only six cases of the non-irradiated variety. In this same store, irradiated grapefruit and juice oranges outsold non-irradiated products by a ratio of nine to one.[14]

Other irradiated food products have been successfully marketed in the United States. In 1986, irradiated mangoes were sold in Miami Beach, Florida.[12] In 1993, irradiated poultry was sold in both Miami Beach and Chicago, also with favorable results. One retailer stated that the most common complaint with the irradiated poultry was the package size; consumers preferred 1 to 1½ pound packages, rather than the 4-5 pound packages that were available.[15]

Finally, it is important to gauge how much consumers are willing to pay for irradiated foods. As stated earlier, the cost of irradiation is relatively small. While it has been shown that consumers are willing to buy irradiated foods, it remains to be seen exactly how much consumers are willing to pay for the added protection against disease. A 1992 study showed that the average consumer was willing to pay up to $0.81, several times greater than the actual cost of irradiation, to eliminate the risk of foodborne illness.[16] However, a more detailed comprehensive study of consumer attitudes is still needed before food irradiation can take a prominent role in the food processing industry.

ADDRESSING CONSUMER CONCERNS

Obviously, the most common question has about irradiated food is, "Is it safe?" After endorsements by the Food and Drug Administration, World Health Organization, American Medical Association, and many other national and international organizations, it may seem unnecessary to even ask this question. However, the consumer needs to be informed of the safety issues involved in the irradiation process. Table 4 shows a list of questions asked by the FDA to establish the safety of irradiated foods.[1]

Table 4 Information Required by the FDA to Establish the Safety of Irradiated Food

Considerations	*Question(s)*
Radiological Safety	Will radioactivity be induced in the food?
Toxicological Safety	Is there evidence of any adverse toxicological effects that can be attributed to toxic substances produced by irradiating the food? What should be tested? What tests provide useful information?
Microbiological Safety	Can irradiation mutate microorganisms, producing more virulent pathogens? Will irradiation reduce the numbers of spoilage microorganisms, allowing pathogens to grow undetected, without competition?
Nutritional Adequacy	Does irradiation under the proposed conditions of use result in a significant loss of any nutrient in the food? Is the food proposed for irradiation an important dietary source of the affected nutrient?

Obviously, if the answers to these questions have been enough to satisfy the FDA, irradiated food should be safe. However, it is important to relate this information to the public and allow them to make informed decisions on the issue. To date, the public has been relatively uninformed about irradiation, with over 90% feeling that they have not seen enough information to make an informed decision and 80% unsure of whether or not they have been exposed to irradiated products.[14]

Beyond the question of food safety is the question of process safety. Are the irradiation facilities safe? Fear and pessimism have become the expected public response to anything involving nuclear technology. The main reasons for this are the complexity of the technology and the fact that most people have relatively little knowledge about how it actually works.[10] The public must be convinced not only of the safety of the products, but the safety of the process itself. Fortunately, the technical issues have all been addressed by studies on food safety and irradiation. However, the task of educating the public can not be taken lightly. The following list represents some of the more common questions posed by the public and how to answer them.

- **Does irradiation make food radioactive?**

  No, irradiation does not make food radioactive. Gamma radiation does not leave any residual radiation in the irradiated products. In addition, there is no physical contact between the product and the radiation source, which eliminates the possibility of contamination. A small number of harmless free radicals are produced by irradiation, similar to those produced by cooking.[16]

In over 30 years of testing, no substances unique to irradiated foods have been found.[3]

- **Are irradiated foods safe?**

  Yes, irradiated foods are safe. The radiological, toxicological, and microbiological effects of irradiation have all been extensively studied, and safety questions have been answered to the satisfaction of the FDA. In fact, the FDA has recommended that foods irradiated to low doses (less than 1 kGy) or consumed only in small quantities be exempted from toxicological testing because the effects of irradiation are of no health concern. Foods irradiated to higher doses and consumed in significant quantities are tested on a case by case basis before gaining FDA approval.[11]

- **What effect does irradiation have on nutritional values of food?**

  Nutritional studies have shown that low-dose (less than 1 kGy) irradiation has no noticeable effect on the nutritional value of foods.[3] In addition, levels of macronutrients including proteins, carbohydrates, and fats are stable at irradiation doses up to 10 kGy. Other vitamins are affected somewhat by irradiation, but these losses are much less than those from other processes, such as cooking.[16] Changes in nutritional values due to irradiation are dependent on several factors, including radiation dose, type of food, packaging, temperature, and oxygen exposure during irradiation.[3] In most cases, irradiating at low temperatures in an oxygen-free environment will minimize vitamin losses.[17]

- **Are irradiation facilities safe?**

Yes, irradiation facilities are safe. A 1992 article summarized the safety of irradiation facilities in the following paragraph:

> "A food irradiation plant would not endanger a community any more than do the medical products irradiation plants and more than 1000 hospital radiation therapy units now operating in the United States, nor would it pose any more hazard to a community than the hundreds of industrial X-ray units currently operating in many communities across the country."[3]

In the United States, there are currently more than 40 irradiation facilities that sterilize medical instruments and supplies. Food irradiation facilities would be similar to these existing plants, mainly because the licensing requirements are similar.[3] Over the past 25 years the few accidents that have occurred in irradiation facilities have all been due to workers deliberately bypassing safety systems and disregarding proper operating procedures.[17]

The irradiation room is surrounded by concrete walls 2-3 meters thick, including the walls and ceiling. The walls act as a biological shield, preventing radiation exposure to both workers and the public.[3] Radiation dose limits for both plant workers and the public are set by the Nuclear Regulatory Commission. A system of interlocks prevents entry into the irradiation room when the source is exposed, eliminating the risk of accidental radiation exposure.[17, 18]

A nuclear 'meltdown' or explosion could never occur in a gamma irradiation facility. Cobalt-60 is a gamma emitter and cannot produce neutrons, which are required for a nuclear 'chain reaction' to occur. Also, without neutrons materials can not be made radioactive, eliminating the problem of radioactive waste accumulation. The Cobalt-60 itself decays over time and is returned to the supplier after the level of radioactivity drops below a certain point, which is determined according to the application of the irradiator.

- **Is the transport of the Cobalt-60 source material safe?**

  Yes, measures have been taken to ensure that the transport of radioactive material is safe. The Cobalt-60 pencils are shipped in lead-shielded steel casks designed to meet national and international standards as set by the NRC and the International Atomic Energy Agency (IAEA) respectively.[17, 18] Between 1955 and 1988 over one million shipments of radioisotopes for industrial, medical, and research purposes were made in North America. Very few accidents occurred involving these shipments and none resulted in any release of radiation into the environment. This far exceeds the safety records of other industries shipping hazardous materials.[17] The shipping casks undergo rigorous destructive testing, as follows, before they are certified for use:

  - Pierce test. The cask is dropped form a height of three feet onto a six inch diameter steel pin.

- Drop test. The cask is dropped from a height of thirty feet onto an unyielding surface.
- Flame test. The cask is exposed to temperatures of at least 1472 °F for 30 minutes.

After completion of these tests, the cask must still retain a large percentage of its original shielding capacity. Only after completion of these tests can a container be certified for use in shipping radioactive materials.

CONCLUSIONS

Irradiation is a promising technology for the food processing industry. With the recent public concern over foodborne illnesses, it is clear that an additional line of defense is needed against pathogens like *Escherichia Coli* O157:H7 and *Salmonella*. Irradiation has been shown to be effective in eliminating these and other foodborne pathogens. In addition, irradiation has been shown to lengthen the shelf life of many food products, which could help eliminate food losses due to spoilage, particularly in developing countries. With the increasing concern over the safety of chemical fumigants, new methods are clearly needed to ensure the safety of the world food supply.

Obviously, the addition of a new step in the food production process will increase the cost of food. However, the cost of irradiation is generally small, and irradiation is often more cost-effective than other methods of food pasteurization and preservation. The main concern from an economic standpoint is whether the public is willing to purchase and eat irradiated foods. Studies have shown that a majority of consumers would be willing to try irradiated foods, but education and marketing efforts are clearly needed before food irradiation will be successful on a widespread basis.

REFERENCES

1. Olson, Dennis G., "Irradiation of Food," *Food Technology* 52(1): 56-62.
2. Thayer, Donald W., Edward S. Josephson, et al., “Radiation Pasteurization of Food,” Council for Agricultural Science and Technology, April 1996.
3. Crawford, Lester M. and Eric H. Ruff, “A Review of the Safety of Cold Pasterurization through Irradiation,” *Food Control* 7(2): 87-97.
4. Shultis, J. Kenneth and Richard E. Faw, *Radiation Shielding,* Prentice Hall PTR, NJ, 1996.
5. Durante, Raymond, Class Lecture, *Food Irradiation Facilities,* Nuclear Engineering 472, University of Tennessee, February 11, 1998.
6. Loaharanu, Paisan, "Cost/Benefit Aspects of Food Irradiation," *Food Technology* 48(1): 104-108.
7. Loaharanu, Paisan, "Status and Prospects of Food Irradiation," *Food Technology* 48(5): 124-131.
8. Kunstadt, Peter and Colyn Steeves, *Economics of Food Irradiation,* Food Irradiation Division, Nordion International Inc. Kanata, Ontario, Canada.
9. Bird, William, Scott Brame, et al., *Conceptual Design of a Food Irradiation Facility*, April 1998.
10. Bord, Richard J. and Robert E. O’Connor, “Who Wants Irradiated Food? Untangling Complex Public Opinion,” Food Technology 43(10): 87-90.
11. Schutz, Howard G., Christine M. Bruhn, and Katherine V. Diaz-Knauf, “Consumer Attitude Toward Irradiated Foods: Effects of Labeling and Benefits Information,” *Food Technology* 43(10): 80-86

12. The National Food Safety Database, "Facts About Food Irradiation: Irradiated Foods and the Consumer," http://www.foodsafety.org/sf/sfo077.htm.
13. Marcotte, Michelle, "Irradiated Strawberries Enter the U.S. Market," *Food Technology* 46(5): 80-86.
14. Pszczola, Donald, "Irradiated Produce Reaches Midwest Market," *Food Technology* 47(5): 89-92.
15. Pszczola, Donald, "Irradiated Poultry Makes U.S. Debut in Midwest and Florida Markets," *Food Technology* 47(11): 89+.
16. Institute of Food Technologists, *Food Irradiation*, December 1997.
17. International Consultative Group on Food Irradiation, *Facts about Food Irradiation*.
18. MDS Nordion, "Safety Considerations in the Operation of Gamma Processing Facilities," http://www.mds.nordion.com/source/research/safety.html.